Predicting the Fire Performance of Buildings: Establishing Appropriate Calculation Methods for Regulatory Applications[†]

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Abstract
A recently organized effort in CIB W14 on Engineering Evaluation of Building Fire Safety is examining the various quantitative methods being promulgated to underpin performance-based codes or for determining equivalency with the implied performance of existing prescriptive codes. These methods share many common features and all recognize the range of fire models and calculational methods that the fire safety engineering profession have begun to embrace as their technical foundation.

The broad range of assumptions inherent in the available methods as well as the data required to utilize them raises some interesting legal, moral, and ethical questions about their appropriateness in applications where legal considerations are involved. Many fire-related computations have no exact solutions, so any calculation represents an approximation. Thus, one can ask, where law defines a minimum level of performance, how far must the fire safety engineer go to minimize uncertainty in a calculation intended to verify compliance? The variability of fire means that there are no inherently "correct" answers against which to define accuracy; and fire experiments involve measurement uncertainties as well as approximations used to reduce the data which often have similar form to the calculations we wish to verify.

These methods all focus on managing fire risk, and their successful application depends on assessing the acceptable level of risk implied by the current codes. From a legal standpoint it cannot be asserted that society accepts current levels of losses because there is no public outcry. Thus, how can acceptable levels of risk be determined when regulatory authorities and legislators are uncomfortable with the notion that there is no zero risk so some fatalities are inevitable?

This paper explores these questions from the perspective of the fire scientist, the practicing engineer, and the regulatory official. The fire scientist needs to be explicit about the impact of assumptions on the applicability of the results to regulatory uses. The engineer needs to utilize methods and assumptions which are justified by the application and to assess the sensitivity and uncertainty implications. The regulatory official must insist on appropriate and properly documented methods. Models and calculations incorporated into codes of practice, handbooks, or the codes themselves must be reviewed, validated, documented, and approved for use in specific manners and by qualified persons. Levels of risk acceptable to society in specific occupancies must be established. Until these issues are resolved, the transition to performance-based codes cannot be made with confidence.

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Introduction

The use of fire models and other predictive methods are becoming common means of supporting the design and arrangement of fire protection features to code officials. Typically, this is done under existing provisions in the codes for "equivalency" to the prescriptive requirements therein. This practice is most prevalent with respect to unique buildings or large projects where variation from normal practice is more common. The result is that the code official, faced with the application of a new engineering method in a high profile project, can experience a high degree of discomfort without some independent verification that the analysis has been done properly.

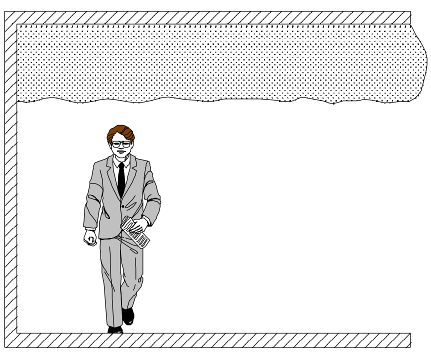
It is for these reasons that this paper was written -- to provide some guidelines for the code official to use in making an initial determination of whether an alternative design analysis is credible. The comments herein are based on the author's own experience in assessing alternate design analyses for several high profile projects and considerable experience in the development and application of fire models.

Key Factors in an Analysis

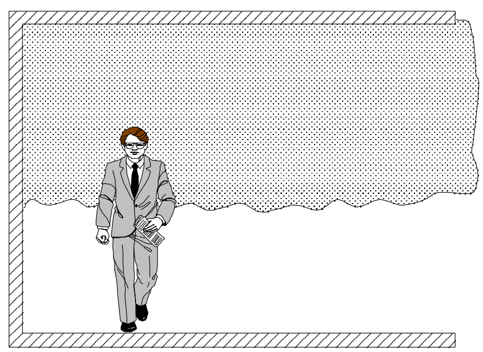
In performing a calculation to assess equivalency to code provisions for safe evacuation of building occupants several steps are required to assure a valid result. These include:

1. Establish the acceptance criteria.
2. Select appropriate fire models/methods.
3. Select design fire(s).
4. Perform an evacuation calculation.
5. Account for uncertainty.
6. Reality check.

In the following sections each of these steps will be discussed in detail so that the objective of each as well as the overall process can be evaluated.



The conservative assumption is that the person is safe until the smoke layer reaches head height.



Actually, people can continue to move through smoke as long as it is cool enough and light enough to see through. Such limits on temperature and smoke density have been incorporated into some egress models and provide valid results.

Establish the Acceptance Criteria

The primary purpose of fire safety code requirements is to allow for safe egress by all building occupants. Thus, the vast majority of alternative design calculations involve egress analysis. This is typically in two parts -- an estimate of the fire development/smoke filling time which establishes the time available for safe egress; and an estimate of the evacuation time needed by the maximum population expected in the exposed area. If time available is greater than the time needed, the occupants are safe and the building complies with the intent of the code.

For the first part of the calculation, the conservative assumption is normally used -- that once the smoke layer fills down to head height (usually 1.5 meters or 5 feet from the floor) escape is no longer possible. In fact, the models can predict the increase in smoke density within the layer (either upper or lower) so that a specified limit either of smoke level or visibility distance can be used. Other than for slowly developing fires, which are not normally used as design fires, or situations where little buoyant layering is expected, there will not be much difference with the conservative assumption.

There are also some situations where egress is not the objective or at least not the only one. In some industrial occupancies (nuclear power or chemical processing plants) the public safety consequences of a fire lead to code requirements intended to prevent exposure of critical systems or processes. In occupancies where persons have limited mobility (health care, correctional, and some board and care) the codes may envision "protection in place." In both of these instances only the filling time calculation is necessary and it may be desirable to make some estimate of the susceptibility of the critical equipment or people to damage. Again, models that do this are available.

Select Appropriate Models/Methods

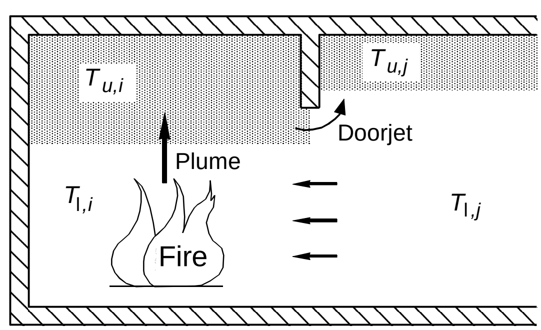
Fire Models

A recent survey [1] documented 62 models and calculation methods that could be applied to these uses. Thus the need is to determine which ones are appropriate to a given situation and which are not. The key to this decision is a thorough understanding of the assumptions and limitations of the individual model or calculation and how these relate to the situation being assessed.

Fire is a dynamic process of interacting physics and chemistry; so predicting what is likely to happen under a given set of circumstances is daunting. The simplest of predictive methods are the (algebraic) equations. Often developed wholly or in part from correlations to experimental data, they represent at best, estimates with significant uncertainty. Yet under the right circumstances they have been demonstrated to provide useful results; especially where used to assist in setting up a more complex model. For example, Thomas' Flashover correlation [2] and the MQH Upper Layer Temperature correlation [3] are generally held to provide useful engineering estimates.

Where public safety is at stake, it is inappropriate to rely solely on such estimation techniques for the fire development/smoke filling calculation. Here, only fire models should be used. Single room models are appropriate where the conditions of interest are limited to a single, freely connected space. Where the area of interest involves more than one space, and especially where they are on more than one floor, multiple compartment models should be used. This is because the interconnected spaces interact to influence the fire development and flows.

Many single compartment models assume that the lower layer remains at ambient conditions (e.g., ASET [4]). Since there is little mixing between layers in a room (unless there are mechanical systems) these models are appropriate. However, significant mixing can occur in doorways, so multiple compartment models should allow the lower layer to be contaminated by energy and mass.



Zone models assume that fire gases collect in layers that are internally uniform.

The model should include the limitation of burning by available oxygen. This is straightforward to implement (based on the oxygen consumption principal) and is crucial to obtaining an accurate prediction for ventilation controlled burning. For multiple compartment models it is equally important for the model to track unburned fuel and allow it to burn when it encounters sufficient oxygen and temperature. Without these features the model concentrates the combustion in the room of origin, overpredicting conditions there and underpredicting conditions in other spaces.

Heat transfer calculations take up a lot of computer time, so many models take a shortcut. The most common is the use of a constant "heat loss fraction" which is user selectable (e.g, CCFM [5]). The problem is that heat losses vary significantly during the course of the fire. Thus, in smaller rooms or spaces with larger surface to volume ratios where heat losses are significant this simplification is a major source of error. In large, open spaces with no walls or walls made of highly insulating materials the constant heat loss fraction may produce acceptable results, but in most cases the best approach is to use a model that does proper heat transfer.

Another problem can occur in tall spaces like atria. The major source of gas expansion and energy and mass dilution is entrainment of ambient air into the fire plume. It can be argued that, in a very tall plume, this entrainment is constrained; but most models do not include this. This can lead to an underestimate of the temperature and smoke density and an overestimate of the layer volume and filling rate -- the combination of which may give predictions of egress times available that are either greater or less than the correct value. In the model CFAST [6], this constraint is implemented through an initial limitation on the height to which the plume rises based on its buoyancy.

Documentation
Only models which are rigorously documented should be allowed in any application involving legal considerations, such as in code enforcement or litigation. It is simply not appropriate to rely on the model developer's word that the physics is proper. This means that the model should be supplied with a Technical Reference Guide which includes a detailed description of the included physics and chemistry with proper literature references, a listing of all assumptions and limitations of the model, and estimates of the accuracy of the resulting predictions based on comparisons to experimental data. Public exposure and review of the exact basis for a model's calculations, internal constants, and assumptions are necessary for it to have credibility in a regulatory application.

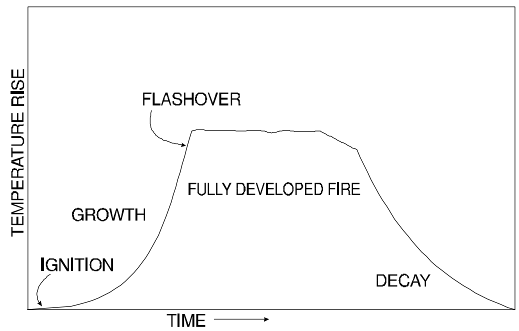
While it is not necessary for the full source code to be available, the method of implementing key calculations in the code and details of the numerical solver utilized should be included. This documentation should be freely available to any user of the model and a copy should be supplied with the analysis as an important supporting document.

Input Data
Even if the model is correct the results can be seriously in error if the data input to the model does not represent the condition being analyzed. Proper specification of the fire is the most critical, and will be addressed in detail in the following section on selecting the design fire(s).

Next in importance is specifying sources of air supply to the fire -- open doors or windows, but also cracks behind trim or around closed doors are important. Most (large) fires of interest quickly become ventilation controlled; making these sources of air crucial to a correct prediction. The most frequent source of errors by novice users of these models is to underestimate the combustion air and underpredict the burning rate.

Other important items of data include ignition characteristics of secondary fuel items and the heat transfer parameters for ceiling and wall materials. In each case, the alternative design analysis should include a listing of all data values used, their source (what apparatus or test method was employed and what organization ran the test and published the data), and some discussion of the uncertainty of the data and its result on the conclusions (see section, Account for Uncertainty).

Select Design Fire(s)
Along with selecting an appropriate model, choosing a relevant set of design fires with which to challenge the design is crucial to conducting a valid analysis. The purpose of the design fire is similar to the assumed loading in a structural analysis -- to answer the question of whether the design will perform as intended under the assumed challenge. Keeping in mind that the greatest challenge is not necessarily the largest fire (especially in a sprinklered building), it is helpful to think of the design fires in terms of their growth phase, steady-burning phase, and decay phase.



Growth
The primary importance of the appropriate selection of the design fire's growth is in obtaining a realistic prediction of detector and sprinkler activation, time to start of evacuation, and time to initial exposure of occupants. Thus this is the most important to an egress analysis which makes up the majority of alternate design analyses.

In 1972, Heskestad first proposed that for these early times, the assumption that fires grow according to a power law relation works well and is supported by experimental data [7]. He suggested fires of the form:

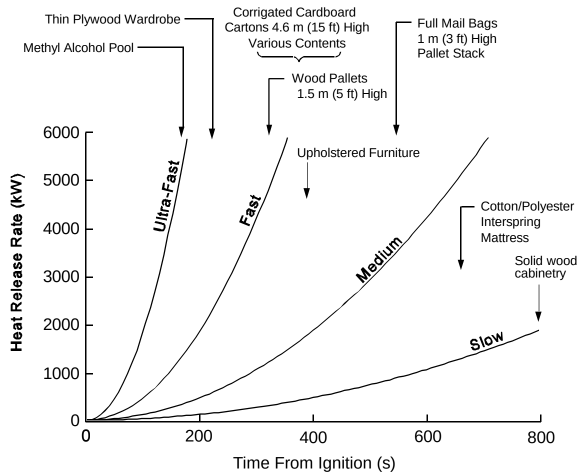
$$\dot{Q} = \alpha t^n$$

where: $\dot{Q}$ is the rate of heat release (kW)
α is the fire intensity coefficient (kW/s^2)
t is time (s)
n is 1,2,3

Later, it was shown that for most flaming fires (except flammable liquids and some others), n=2, the so-called T-squared growth rate was an excellent representation [8]. A set of specific T-squared fires labeled slow, medium, and fast, with fire intensity coefficients (α) such that the fires reached 1055 kW (1000 BTU/s) in 600, 300, and 150 seconds, respectively were proposed for design of fire detection systems [9]. Later, these specific growth curves and a fourth called "Ultra-fast" [10] which reaches 1055 kW in 75 seconds, gained favor in general fire protection applications.

This specific set of fire growth curves have been incorporated into several design methods such as for the design of fire detection systems in the *National Fire Alarm Code* [11]. They are also referenced as appropriate design fires in several, international methods for performing alternative design analyses in Australia and Japan, and in a product fire risk analysis method published in this country [12]. While in the Australian methodology the selection of growth curve is related to the fuel load (mass of combustible material per unit floor area) this is not appropriate since the growth rate is related to the form, arrangement, and type of material and not simply its quantity. Consider 10 kg (22 pounds) of wood; arranged in a solid cube, sticks arranged in a crib, and as a layer of sawdust. These three arrangements would have significantly different growth rates while representing identical fuel loads.

This set of T-squared growth curves are shown on the next page. The slow curve is appropriate for fires involving thick, solid objects (solid wood table, bedroom dresser, or cabinet). The medium growth curve is typical of solid fuels of lower density (upholstered furniture and mattresses). Fast fires are thin, combustible items (paper, cardboard boxes, draperies). Ultra-fast fires are some flammable liquids, some older types of upholstered furniture and mattresses or other highly volatile fuels.



In a highly mixed collection of fuels selecting the medium curve is appropriate as long as there is no especially flammable item present. It should also be noted that these T-squared curves represent fire growth starting with a reasonably large, flaming ignition source. With small sources there is an incubation period before established flaming which can influence the response of smoke detectors (resulting in an underestimate of time to detection). This can be simulated by adding a slow, linear growth period until the rate of heat release reaches 25 kW.

Steady burning

Once all of the surface area of the fuel is burning the heat release rate goes into a steady burning phase. This may be at a sub-flashover or a post-flashover level -- the former will be fuel controlled and the latter ventilation controlled. It should be obvious from the model output (for oxygen concentration or upper layer temperature) in which condition the fire is burning.

Most fires of interest will be ventilation controlled; and this is a distinct advantage since it is easier to specify sources of air than details of the fuel items. This makes the prediction insensitive to both fuel characteristics and quantity since adding or reducing fuel simply makes the outside flame larger or smaller. Thus, for ventilation controlled situations the steady burning region can be specified at any level that results in a flame out the door and the heat released inside the room will be controlled to the appropriate level by the model's calculation of available oxygen. For the much smaller number of fuel controlled scenarios values of heat release rate per unit area at a given radiant exposure (from the Cone calorimeter, ASTM E-1354) can be found in handbooks and used with an estimate of the total fuel area.

Decay

The burning rate declines as the fuel is exhausted. This decline is often specified as the inverse of the growth curve; this means that fast growth fuels decay fast and slow decay slow. It is often assumed that the point at which decay begins is when 20% of the original fuel is left. While these are assumptions, they are technically reasonable.

Of course if a sprinkler system is present this decay will proceed as the fire is extinguished by the water. A simple assumption is that the fire immediately goes out; but this is not conservative. It is better to use a recent NIST study which documents a (conservative) linear diminution in burning rate under the application of water from a sprinkler [13]. Since the combustion efficiency is affected by the application of water, the use of values of soot and gas yields appropriate for post-flashover burning would represent the conservative approach in the absence of experimental data.

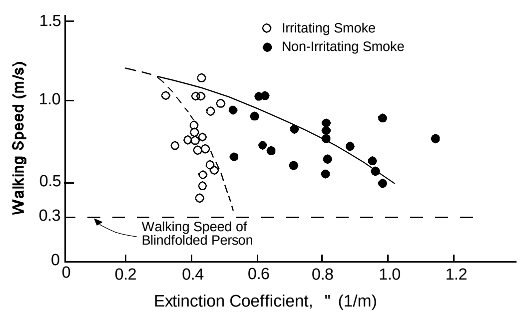
Evacuation calculations

The prediction of the time needed by the building occupants to evacuate to a safe area is performed next, and compared to the time available from the previous steps. Whether the evacuation calculation is done by model or hand calculation it must account for several crucial factors. First, unless the people see the actual fire there is time required for detection and notification **before** the evacuation process can begin. Next, unless the information is compelling (again, they see the actual fire) it takes time for people to decide to take action. Finally, the movement begins. All of these factors require time, and that is the critical factor. No matter how the calculation is done, **all** of the factors must be included in the analysis to obtain a complete picture. An excellent discussion of this topic is found in Pauls' [14] and Bryan's [15] chapters in the SFPE Handbook.

Models

The process of emergency evacuation of people follows the general concepts of traffic flow. There are a number of models which perform such calculations and which may be appropriate for use in certain occupancies. Most of these models do not account for behavior and the interaction of people (providing assistance) during the event. This is appropriate in most public occupancies where people do not know each other. In residential occupancies family members will interact strongly and in office occupancies people who work together on a daily basis would be expected to interact similarly. The literature reports incidents of providing assistance to disabled persons, again especially in office settings [16]. If such behavior is expected it should be included as it can result in significant delays in evacuating a building.

Another situation where models are preferred to hand calculations is with large populations where congestion in stairways and doorways can cause the flow to back up. However this can be accounted for in hand calculations as well. Crowded conditions as well as smoke density can result in reduced walking speeds [17]. Care should be exercised in using models relative to how they select the path (usually the *shortest* path) over which the person travels. Some models are *optimization* calculations which give the best possible performance. These are inappropriate for a code equivalency determination.



A person's walking speed decreases in dense smoke until they move as slowly as if blindfolded.

Hand calculations

Luckily, evacuation calculations are generally simple enough to be done by hand. The most thorough presentation on this subject (and the one most often used in alternate design analysis) is that of Nelson and MacLennen in [18]. Their procedure explicitly includes all of the factors discussed previously along with suggestions on how to account for each. They also deal with congestion, movement through doors and on stairs, and other related considerations.

Account for Uncertainty

This refers to dealing with the uncertainty which is inherent in any prediction. In the calculations this uncertainty derives from the models and from the input data. In evacuation calculations there is the added variability of any population of real people. In building design and codes the classic method of treating uncertainty is with safety factors. A sufficient safety factor is applied such that, if all of the uncertainty resulted in error in the same direction the result would still be safe.

In the prediction of fire development/filling time the intent is to select design fires which provide a *worst likely* scenario. Thus, a safety factor is not needed here unless assumptions or data are used to which the predicted result is very sensitive. In present practice for the evacuation calculation a safety factor of 2 is generally recommended to account for unknown variability in a given population.

The analysis report should include a discussion of uncertainty. This discussion should address the representativeness of the data used and the sensitivity of the results to data and assumptions made. If the sensitivity is not readily apparent, a sensitivity analysis (vary the data to the limits and see whether the conclusions change) should be performed. This is also a good section in which to justify the appropriateness of the model or calculation method in the manner discussed previously.

Reality Check

The last step in any calculated analysis is the reality check. If a model or calculation produces a result which defies logic there is probably something wrong. Cases have been seen where the model clearly produced a wrong answer (the temperature predicted approached the surface temperature of the sun) and those where it initially looked wrong but was not (a **dropping** temperature in a space adjacent to a room with a growing fire was caused by cold air from outdoors being drawn in an open door). Conversely, if the result is consistent with logic, sense, and experience it is probably correct.

This is also a good time to consider if the analysis addressed all of the important scenarios and likely events. Were all the assumptions justified and uncertainties addressed sufficiently to provide a comfort level similar to that obtained when the plans review shows that all code requirements have been met?

Obtaining Help

For the large, high profile project, the public outcry likely to occur if something goes wrong presents a risk which may demand a higher level of confidence. The code official may feel compelled to obtain an independent opinion about the appropriateness of the analysis. This is reasonable to expect.

Qualified engineering firms exist in nearly any area of the country, although they will need to be paid. The model codes make provision for the submitter to pay for "special studies" needed; and this could include such reviews. Several universities have fire science or fire protection engineering programs where faculty can serve as experts. Finally, NIST experts are available answer questions from code officials about the models or data which have been developed here.

In Japan, a formal system was put into place for this purpose. For major projects where alternate design analyses have been performed, the local code official can call on an expert panel drawn from government and university experts for consultation. These experts advise the code official who ultimately makes the final decision. A similar system could be organized through organizations such as NIBS, NCSBCS, or CABO if there is a demand for such from the code enforcement community.

Certification of Methods

Considering the complexity of the methods and the criteria presented in this paper against which these methods should be judged, most code officials will not be comfortable with making decisions about the appropriateness of a model's physics or some complex assumptions. But for projects where obtaining outside advice is not practical this is exactly what would be required. For these cases the answer may lie in another approach familiar to the regulatory community -- third party certification.

Criteria such as those presented in this paper might be used to initiate a draft standard for models and calculations appropriate to alternate design analysis. Following review and a consensus process some organization might then certify or sanction specific models or methods for such, when used under specified conditions. This might be accomplished through the model code process since these codes already contain "sanctioned methods" for doing structural calculations. Such a process has been undertaken in New Zealand where a software package has been sanctioned and directly produces a certified report suitable for submittal directly to the code official.

Concluding Remarks
Alternate design calculations provide a way to achieve design flexibility and code equivalence based on performance. The advantages of such a system are widely recognized and research is underway all around the globe to formalize the process through national and international standards. Use in this country is growing as well.

By applying the information presented in this paper we hope that the level of comfort of the code official faced with assessing these calculations will be high and code officials will be able to deal better with the alternate design process.

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